Turbulence Dynamics In Irregular Breaking Waves

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LONG-TERM GOALS

My long-term goals are to provide a detailed picture of the breaking and decay of irregular waves in a laboratory surf zone, and of the generation and evolution of the related turbulent flow fields.

OBJECTIVES

The objectives of this project are:

1. To understand the effects of incident wave spectrum on the wave characteristics and turbulence dynamics inside the surf zone.

2. To determine the effect of offshore bars on the wave breaking process.

3. To elucidate the properties of wave breaking induced vortex structures.

APPROACH

A new 25 m long, 0.9 m wide and 0.75 m deep tilting flume with Plexiglas side walls and bottom will be commissioned in the Fluid Mechanics Laboratory at South Dakota State University in November 2001. This flume will be equipped with a programmable random wave generator that has active wave absorption to minimize long wave reflection from the wave paddle. Irregular waves will be generated and wave breaking will be induced on a plane slope. Submerged solid objects will be installed on the slope to represent natural bars. The laboratory experiments will be carried out over a wide range of incident wave conditions developed from the TMA spectrum by varying the spectral significant wave height, spectral peak period, spectra shape parameters and beach slope. The experiments will involve detailed measurement of water surface elevations inside the surf zone using an array of capacitance wave gages, measurement of turbulent flow velocities on a grid using a three-component laser-Doppler anemometer, measurement of instantaneous three-dimensional velocity fields in a plane under the breaking waves using a stereoscopic particle image velocimetry system, and videotape recording of the surf zone. The measured data will be used to improve our understanding of the dynamics of surf zone turbulence through an experimental investigation of the Reynolds-averaged momentum and energy equations, to determine the dissipation rates and Reynolds stresses in breaking waves, to obtain the ensemble-averaged properties of the surf zone flow field, and to elucidate the spatial and temporal structures of surface breaking-induced vortices.

The first year of this project has been focused on developing techniques for analyzing irregular wave turbulence. Measured data from four irregular wave experiments obtained in a wave flume at Texas A&M University were studied. These experiments included two different wave spectra (broad-band and narrow-band) on two different beach profiles (plane and barred beach). Time-dependent properties of the surf zone flow field were obtained using a wave-by-wave analysis. New experiments are planned for the second year to use wavelet transform to identify coherent structures.

WORK COMPLETED

We have analyzed the surf zone flow field on a 1:35 slope for a broad-band and a narrow-band irregular wave train (Ting, 2001a,b). In these experiments, water particle velocities were measured simultaneously with wave elevations at three cross-shore locations inside the surf zone. The measured data were separated into long-wave and short-wave time series using a Fourier filter. The long-wave time series were used to determine the time-varying water depth and wave-induced current produced by the long waves. The short-wave time series were used with ensemble averaging to determine the surface wave profiles, organized wave-induced velocities and turbulent velocity fluctuations. The locations of wave breaking were determined from videotape recording of the surf zone. The probability distributions of the individual wave heights, wave periods, peak wave velocities, and wave-averaged turbulent kinetic energies and Reynolds stresses were obtained. A wave-by-wave analysis was carried out to obtain the variations of turbulent kinetic energy and Reynolds stress, and of the transport of turbulent kinetic energy by wave and turbulent velocities with time. The vertical structure of the undertow and the velocity profiles under the long waves were also determined.

RESULTS

Figure 1 presents the short-wave height H_i, normalized by the period-averaged water depth, h_i (i = 1,2…N) for the N waves in the narrow-band wave time series. A surf similarity parameter value of 0.20 was determined for the narrow-band waves based on the spectral significant wave height and spectral peak period. Most of the waves in the narrow-band spectrum formed spilling breakers.

Figure 1 shows that the incident waves form several distinct wave groups. The wave-height-to-water-depth ratio of the individual wave H_i/h_i increases to a maximum value of 0.7 to 1.0 at breaking, and then decreases steadily to a constant value of about 0.5 inside the surf zone. Similar values were observed in a spilling regular wave with the same surf similarity parameter value (Ting and Kirby, 1996). It is found that the waves with the smaller initial heights break closer to shore and have higher wave-height-to-water-depth ratios at breaking than the waves with the larger initial heights. It is also found that normalizing the wave height by the time-varying water depth instead of the time-averaged water depth produces a narrow variation in the H_i/h_i ratio in the inner surf zone. Thus, long waves affect the short waves riding on them by changing the local water depth. Figure 1 shows that the level of groupiness inside the surf zone is greatly reduced by the wave breaking process.

Figure 2 presents the period-averaged turbulent kinetic energy k_i for the narrow-band waves. In the outer and middle surf zone, high level of turbulent kinetic energy is found under the waves with the larger initial heights, which are the first waves to break. After most of the waves have broken, the variation of turbulent kinetic energy with time becomes more uniform. The Reynolds stress (not shown) is closely correlated to the turbulent kinetic energy. The Reynolds stress correlation coefficient is smaller at the lower level than at the upper level, consistent with the idea that the free surface is the source of most of the turbulent kinetic energy in breaking waves.

A wave-by-wave analysis was carried out to determine how turbulent kinetic energy varies with time under irregular waves. The results show that in the inner surf zone narrow-band waves have turbulence characteristics similar to those found in a spilling regular wave (Ting, 2001b). Whereas, turbulence characteristics may vary considerably from wave to wave in broad-band waves.

IMPACT/APPLICATIONS

The results of this project will be two-fold:

1. A successful outcome of this project would be a detailed picture of the breaking and decay of irregular waves in a laboratory surf zone, and of the generation and evolution of the related turbulent flow fields on plane and barred beaches.

2. This project would provide the data needed to test and improve detailed models of surf zone breaking processes. This data set should be useful for testing a wide range of surf zone modeling techniques, including both present day models and models that are under long-range development.

TRANSITIONS

This project is complementary to related work in the National Ocean Partnership Program (NOPP) to develop a community model of nearshore waves, current and bathymetric change. Researchers may use the laboratory data for integration, testing and improvement of their surf zone models.

RELATED PROJECTS

1. NSF Grant Number CTS-0078926, "Acquisition of a Multi-Purpose Open-Channel Flume for Water Flow Studies," Francis C. K. Ting et al., South Dakota State University. This equipment grant has provided partial funding for the new flume.

2. N00014-99-1-1051 (NOPP), "Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean," James T. Kirby et al., University of Delaware. We are working with Professor Kirby on the experimental design and data analysis to improve our understanding of the laboratory measurements and to maximize the ability to fully test numerical models with experimental data.

REFERENCES

Ting, F. C. K. and Kirby, J. T. (1996), "Dynamics of surf zone turbulence in a spilling breaker," Coastal Engineering, Vol. 27, pp. 131-160.

PUBLICATIONS

Ting, F. C. K. (2001a), "Laboratory study of wave and turbulence velocities in a broad-banded irregular wave surf zone," Coastal Engineering, Vol. 43, pp 183-208.

Ting, F. C. K (2001b), "Wave and turbulence characteristics in narrow-band irregular breaking waves," submitted to Coastal Engineering.

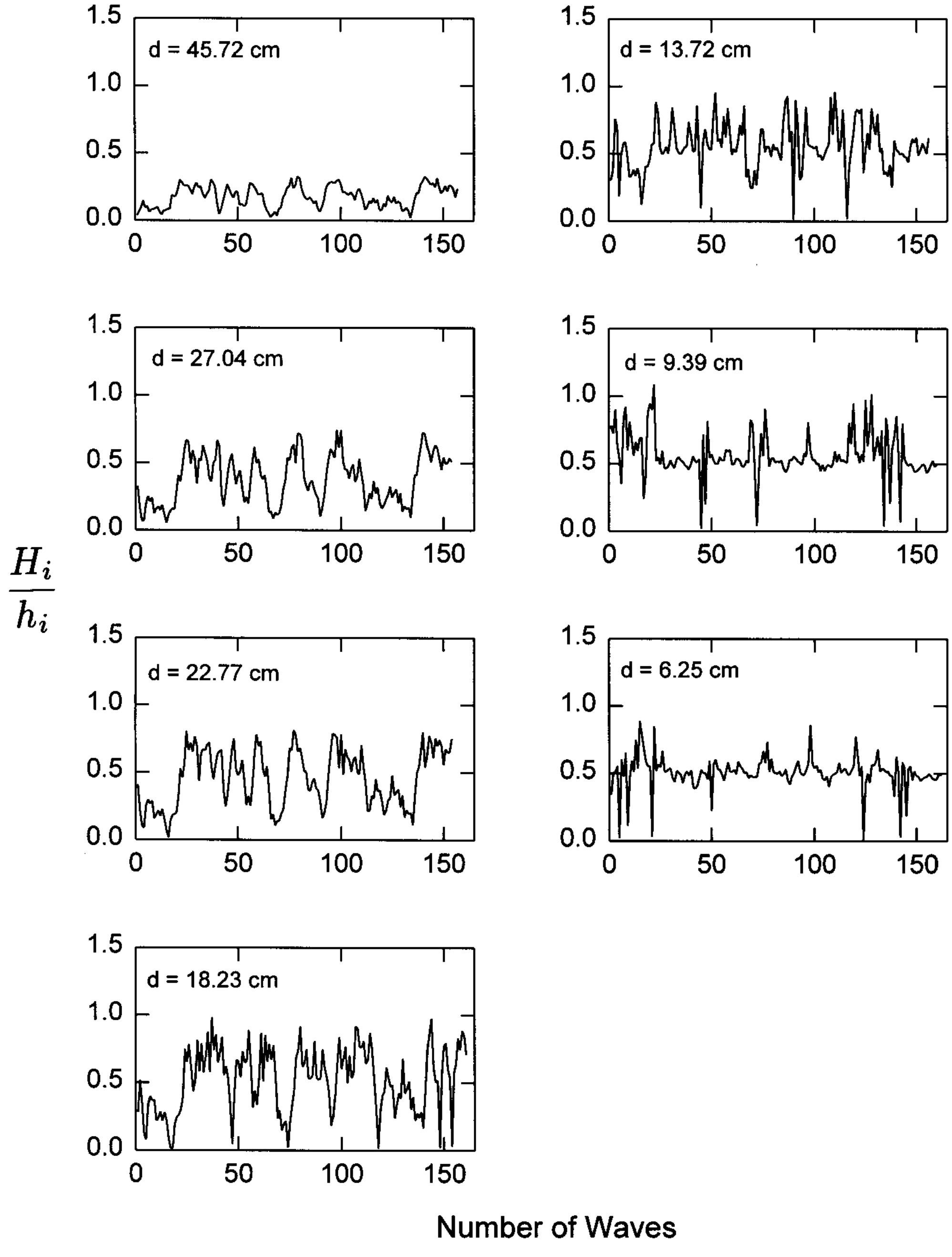

Figure 1. Wave-height-to-water-depth ratio of individual waves in narrow-band irregular wave train at still water depth d = 45.72, 27.04, 22.77, 18.23, 13.72, 9.39 and 6.25 cm. The incident waves form wave groups and the order in which the individual waves break follow closely their initial heights in the groups. At d = 6.25 cm, the wave-height-to-water-depth-ratio of the broken waves has a narrow variation with an average value of 0.51.

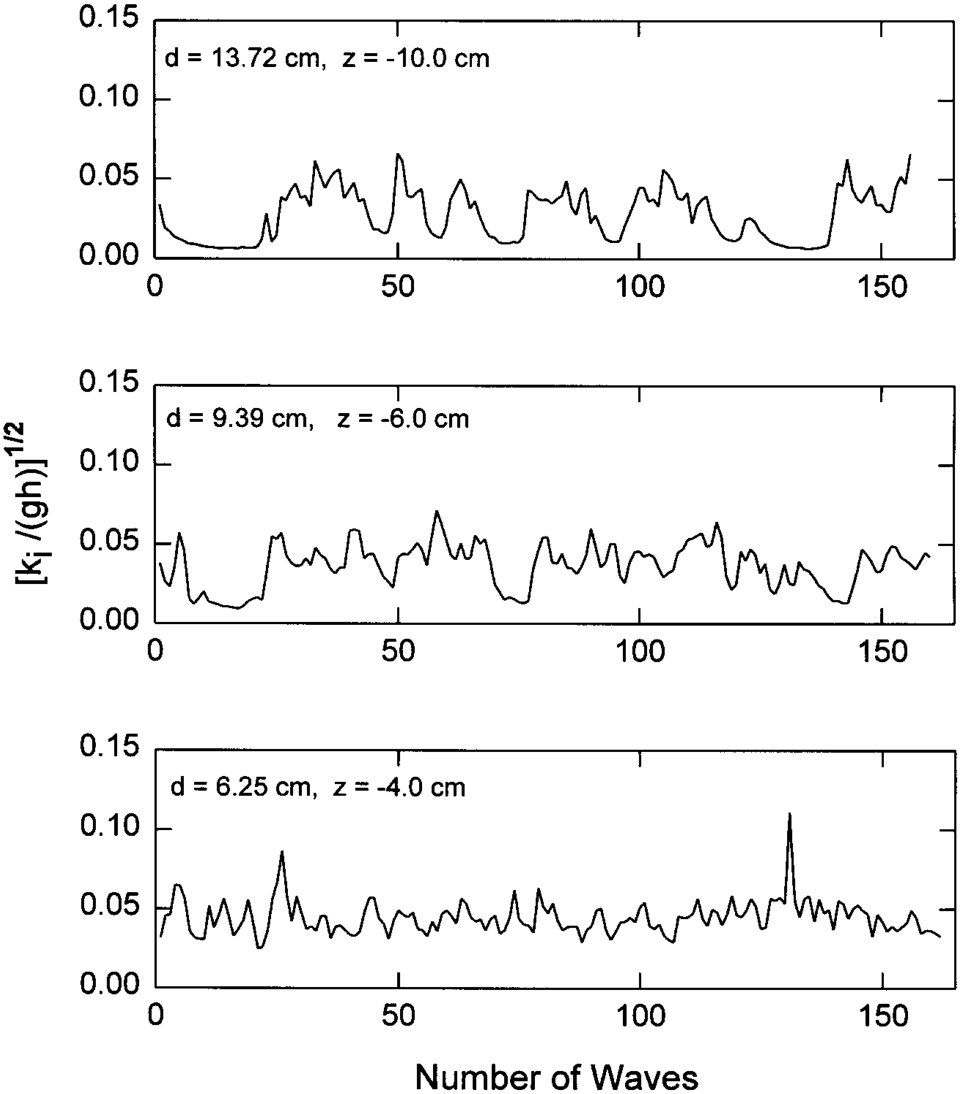

Figure 2. Period-Averaged turbulent kinetic energy at still water depth d = 13.72, 9.39 and 6.25 cm. Turbulent kinetic energy is defined based on the longitudinal and vertical velocity components u' and w'. These measurements taken at the lower level of the water column show that turbulent kinetic energy varies considerably from wave to wave at d = 13.72 and 9.39 cm, but becomes more uniform with time at d = 6.25 cm after most of the waves have broken.